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Final report summarizes research carried out under subject contract and described in two reports: "Cavitation Dynamics. III. Thresholds and Generation of Transient Cavities," dated 25 July 1978 and "Cavitation Dynamics. IV. Collapse of Transient Cavities," dated 28 July 1978.

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Chief of Naval Research
Physics Program Office (Code 421)
Department of the Navy
800 N. Quincy Street
Arlington, Virginia 22217

SUBJECT: Final Report on research carried out under Contract
N00014-76-C-.080

Dear Sir:

The program of research carried out under the subject contract had as its
aim the completion of a series of papers on cavitation dynamics. The two papers
in this series, previously submitted to ONR as reports, have been published as:

1. "Cavitation Dynamics. I. A mathematical formulation," J. Acoust. Soc.
Am. 57, 1379-1396 (1975), hereinafter referred to as CD:I.

2. "Cavitation Dynamics. II. Free pulsations and models for cavitation
bubbles," J. Acoust. Soc. Am. 58, 1160-1170 (1975), hereinafter referred to
as CD:II.

In CD:I, a mathematical formulation was derived for use in obtaining numer-
ical solutions which would give us reliable predictions of the motions of small
cavitation bubbles in a liquid under the influence of an acoustic pressure field.
The set of non-linear differential, integral and algebraic equations in this
formulation took into account the effects of heat conduction, viscosity, com-
pressibility and surface tension. In the second paper, CD:II, this formulation
was used to study the free pulsations of an argon-filled cavity in water, and
the effects of compressibility, heat conduction and viscosity on such quantities
as maximum pressure, maximum temperature, energy dissipation and the non-linear
resonance frequency were determined. Curves showing the non-linear resonance
frequency as a decreasing function of the maximum radius, R_o's of a cavity have
since proved to be of great importance in the research done under this contract.

One of the central concerns of cavitation research has always been the study
of cavitation thresholds. In the past a threshold has usually been defined as a
value of the acoustic pressure amplitude at which some phenomenon associated with
cavitation activity abruptly increased in magnitude. However, Monakhov et al
obtained experimental evidence of a second (and higher) threshold at which an
abrupt decrease in such a phenomenon would occur. There is usually a maximum
in cavitation activity between the two thresholds.

The first part of this research program undertaken with funds allocated to
this contract sought a dynamical explanation for the two cavitation thresholds.
The results are described in the third report of the series:

3. "Cavitation Dynamics. III. Thresholds and the generation of transient cavities," dated 25 July 1978 and hereinafter referred to as CD:III.

Calculation of the maximum pressure in a collapsing cavity and the work done by an expanding cavity under the influence of a periodic pressure field showed that there are indeed dynamical explanations for these two cavitation thresholds. There are two distinct regimes, depending on whether or not the acoustic driving frequency, f_A, is greater than the linear resonance frequency f_0 of the cavity or less than the linear resonance frequency. When f_A is equal to or greater than f_0, neither threshold occurs and the cavity behaves much like a stable cavity defined in CD: II. When f_A is equal to or greater than f_0, quantities such as the maximum pressure will increase with the acoustic pressure amplitude, p_A, but they may be orders of magnitude less than those occurring when the cavity is driven at frequencies less than f_0. In other words, the linear resonance frequency, f_0, is a bad choice of an operating frequency for obtaining a maximum in cavitation activity in a cavitation zone.

When the driving frequency, f_A, is less than the linear resonance frequency, f_0, the first pressure threshold is reached when an increase in the acoustic pressure amplitude, p_A, causes an expansion of a cavity to a maximum radius, R_0, which is so large that collapse of the cavity is controlled by inertial forces in the liquid rather than the various pressure forces acting on the cavity. Once this critical value of R_0 is exceeded, the cavity collapses violently and can be identified as a transient cavity. This finding confirms a similar conclusion for freely pulsating cavities reported in CD:II. The behavior at the first threshold is in marked contrast with the behavior of a cavity for f_A equal to or greater than f_0 where, for all R_0, pressure forces control the motion of the cavity during most of its collapse.

When f_A is less than f_0, the research done under this contract identifies the second cavitation threshold with the non-linear resonance frequency, f_r, of a cavity as calculated in CD:II. At a given frequency, f_A, of the acoustic pressure field, the cavity's maximum radius increases with an increase in the acoustic pressure amplitude, p_A. With increasing R_0, the non-linear resonance frequency, f_r, of the cavity decreases from its linear value, f_0, and when f_r becomes less than the driving frequency, f_A, the cavity ceases to be a transient cavity and both the maximum pressure reached on collapse and the work done by an expanding cavity approach a plateau. In a liquid containing a distribution of "seeds" of gas of various initial radii, this change at the second threshold would result in the decrease of cavitation activity observed by Monakhov et al.

The calculations carried out in CD:II and CD:III were limited to motions in which the effects of compressibility were not too great. This limitation arose from the equations of state used to describe the liquid and the gas within a cavity; the gas was assumed to be perfect and the liquid to be such that the variational pressure was a linear function of the variational density (that is, the speed of sound was a constant). In the second phase of this research, this restriction was removed and "realistic" equations of state used to describe the liquid and the gas within a cavity.

The main objective in this second phase was to find out whether or not there exists an upper limit on the maximum pressures and temperatures reached in a collapsing cavity. The results of the use of "realistic" equations of state to explore this question were described in the fourth paper of this series:

4. "Cavitation Dynamics. IV. Collapse of transient cavities," dated 28 July 1978, hereinafter referred to as CD:IV.

The principal result of this phase of the research is that the use of "realistic" equations of state does not reveal any upper bound on the maximum pressure reached in the collapse of a transient cavity. Pressures of the order of hundreds of kilobars could easily be obtained, provided that the cavity retains its spherical shape throughout the collapse.

However, the interface of a collapsing cavity is normally unstable and tends to break up whenever a perturbation of shape occurs. It is this instability of shape which places a limitation on the violence of collapse. Calculations of the growth of such instabilities were made and indicate that initial conditions have a strong influence on their rate of growth. Any factor that delays the appearance of a perturbation of the surface of a collapsing cavity greatly decreases the rate of growth of the perturbation or may even cause it to decay. It would thus appear that, in a cloud of bubbles in a cavitation zone, the survival of any collapsing bubble until its pressure and temperature reach values predicted in CD:IV would be a statistical phenomenon.

Work on the research described in this final report started on 1 December 1976 and continued through 30 June 1978. The funds allocated to the contract amounted to $20,516 and there were two no-cost extensions. At the termination of the contract there are no unexpended funds. The two reports identified as CD:III and CD:IV are being submitted to the Journal of the Acoustical Society of America for publication.

Sincerely yours,

H.G. Flynn
Principal Investigator
Contract N00014-76-C-1080.

HGF:mca
cc: /dist. list